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The costs and benefits of a nitrogen emission control area in the Baltic and North Seas

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ABSTRACT

The main purpose of this paper is to analyse the socio-economic justification of implementing a Nitrogen Emission Control Area (NECA), starting 2021, for ships in the Baltic Sea and/or the North Sea and English Channel. We analyse the potential for emission reduction, emission control costs, and monetised benefits following the introduction of a NECA. Costs and benefits are compared for 2030. We compile new data on emission control costs for shipping, use the GAINS model for calculations of emission dispersion, and the Alpha-RiskPoll model for estimating monetary values of health impacts. The model results show that costs to conform to the NO_X regulations of a NECA in the Baltic Sea, North Sea or both sea regions would be 111 (100–123), 181 (157–209), and 230 (195–273) million € per year, respectively. Corresponding benefits from reduced emissions are estimated to be 139 (56–294), 869 (335–1882), and 1007 (392–2177) million € per year, respectively. Calculated benefits surpass costs for most scenarios, but less convincingly for a Baltic Sea NECA. Conforming to the NECA regulations by using Liquefied Natural Gas (LNG) propulsion engines is estimated to give the highest net benefits but also the largest variation (costs: 153 (88–238), benefits: 1556 (49–3795) million €/year). The variations are mainly due to uncertainties in the valuation of avoided fatalities and climate impacts. It is concluded that the NECAs for the Baltic and North Seas can be justified using CBA under all but extreme assumptions.

1. Introduction

Air pollution is the largest health risk from environmental causes (World Health Organization, 2014a), mainly driven by human exposure to fine particulate matter with aerodynamic diameter < 2.5 µm ($PM_{2.5}$) (World Health Organization, 2014b). Emissions from combustion engines (including ship engines) contribute to $PM_{2.5}$ in ambient air both with primary particles (black carbon (BC), organic carbon (OC), and other particles) and with secondary particles formed from exhaust gases – mainly nitrogen oxides (NO_x) and sulphur oxides (SO_X). NO_x and SO_x react with ammonia (NH_3) in the atmosphere to form secondary inorganic aerosols, which have been shown to constitute ~30–50% of $PM_{2.5}$ levels in ambient air in northern and central European countries (Putaud et al., 2010). In Europe 2012, ~380,000 premature fatalities occurred due to $PM_{2.5}$ (Lelieveld et al., 2015). The contribution of shipping emissions

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to premature fatalities from $PM_{2.5}$ in ambient air in Europe and other countries in the Mediterranean region in 2012 has been estimated at ~6000–44,000 (Corbett et al., 2007). NO_x emissions from shipping also contribute to acidification, eutrophication, and the formation of ground-level ozone. Without further control the emissions of NO_x to air from shipping in the European seas are projected to soon become larger than land-based emissions (European Environment Agency, 2013). Shipping is also a source of carbon dioxide (CO_2) emissions, and the shipping industry's relative share of anthropogenic CO_2 emissions is also expected to grow significantly if no measures are taken (Eide et al., 2013).

Emissions of air pollutants and greenhouse gases from international shipping are regulated by the International Maritime Organization (IMO) MARPOL convention. The convention applies globally but with regional exceptions for emission control areas (ECA). Stricter regulations apply in these areas. The Baltic Sea (BAS), the North Sea and the English Channel (NSE) are classified as sulphur ECAs (SECAs). From 2015, the emission regulations in SECAs were strengthened to allow no more than 0.1% sulphur by weight in the fuel unless exhaust-gas emission control technology is used to reach corresponding SO_2 emission levels (IMO, 2015). NO_x emissions from shipping are regulated in a three tiered emission standard scheme, with permitted emissions dependent on ship construction year and engine speed. In July 2017, IMO adopted proposals for designation of BAS and NSE as nitrogen ECAs (NECAs), implying that ships keel laid (the date of formal recognition of the start of a ship's construction) after the 1st of January 2021 have to comply with the most strict (Tier III) emission standards (IMO, 2017). The use of Tier III technologies is anticipated to increase costs of emission control from shipping.

Emission reduction has – to various extents – positive impacts on human health and the environment. Through stated preference (willingness to pay) studies and/or through revealed preference studies it is possible to monetize these impacts, which in turn enables comparison of expected monetary benefits and costs of a policy proposal.

For the Baltic and the North Seas, the sea regions studied in this paper, 2010 NO_x emissions are projected to decrease by 27–42% by 2030 through the implementation of NECA (Winnes et al., 2016, Kalli, 2013) while CO_2 emissions are projected to remain stable if no further regulations are put in place (Kalli et al., 2013). Peer-reviewed analyses of the socio-economic impacts of SECAs are more common than for NECAs. Wang and Corbett (2007) conclude that the introduction of a SECA in the western sea areas of the United States has favourable socio-economic benefit/cost (B/C) ratios for both 1.5% and 0.5% as limits for the sulphur content in fuel with the 0.5% limit having the higher B/C ratio. Tzannatos (2010) show that fuel sulphur limits of either 1.5% or 1% in the Mediterranean Sea would imply net socio-economic benefits for society. A report by Bosch et al. (2009) shows that SECA in the Baltic and North Seas by 2020 would imply net socio-economic benefits (B/C ratio 2–26). For NECA for the northern European region recent reports show that a NECA implemented by 2016 in the North Sea would imply benefits about twice as high as costs (Danish Environmental Protection Agency (DEPA), 2012, Hammingh et al., 2012).

In this paper, we add to earlier research by analysing the net socio-economic impacts in 2030 for Europe of a 2021 introduction of NECA for either the Baltic Sea or the North Sea, or for both sea regions, an analysis needed to give scientific support of the decision to implement NECA by 2021. For these sea regions we also analyse the potential for co-benefits or trade-offs between air quality and climate change from the possible use of LNG-fuelled propulsion technologies in new ships – a technology that reduces emissions of most air pollutants (Anderson et al., 2015) – as a means to comply with NECA requirements. Specifically, we focus this paper on two research questions:

- What are the costs and benefits in 2030 of implementing a NECA by 2021 in the Baltic and North seas, jointly and separately?
- Would the results change with an introduction of LNG-fuelled propulsion technologies in new ships, and would this imply co-benefits or trade-offs with greenhouse gas emission control?

2. Method

Cost-benefit analysis (CBA) (Pearce et al., 2006, Boardman et al., 2001) and the impact pathway approach (Bickel and Friedrich, 2005) are used to analyse the net socio-economic benefit of NECA (presented as B/C ratios of benefits from reduced human health and crop damages and costs of emission control and potential climate change impacts). CBA is suitable for analysing environmental policy (Arrow et al., 1996) and plays an important role for air pollution policies (Burtraw et al., 1998; Holland et al., 2000, 2014; Schucht et al., 2015; Wang and Corbett, 2007; Tzannatos, 2010).

In the analysis we integrate new emission and control cost calculations with existing methods for estimating and valuing climate change-, crop growth-, and human health impacts. The analysis is done using scenarios; first a baseline (**BSL**) scenario up until the year 2030 is constructed, followed by four NECA scenarios. The control costs, climate change-, crop growth-, and human health impacts in **BSL** are then compared to the corresponding values in the NECA scenarios. Based on fuel consumption data and average ship age data we construct age-specific fuel use estimates as the basis for all scenarios. Each age group uses a scenario-specific emission control technology which gives scenario-specific emissions and emission control costs. We use a linear emission dispersion model and through calculations of human exposure to ambient $PM_{2.5}$ combined with concentration-response functions recommended by WHO we can calculate human health impacts. These impacts and impacts on crop damages as well as – if applicable – climate impacts are then monetized to enable direct comparison with costs (Fig. 1). The scenarios for 2030 considered in the analysis are described in Table 1.

Uncertainties in costs and benefits are analysed by calculating benefit/cost ratios for low, mid, and high estimates of costs and benefits for each scenario. The full analysis required many steps of calculations, which cannot all be included in this paper. All equations and input data for calculations of emissions and control costs are available in the supplementary material, referred to with the prefix "A" in this text.

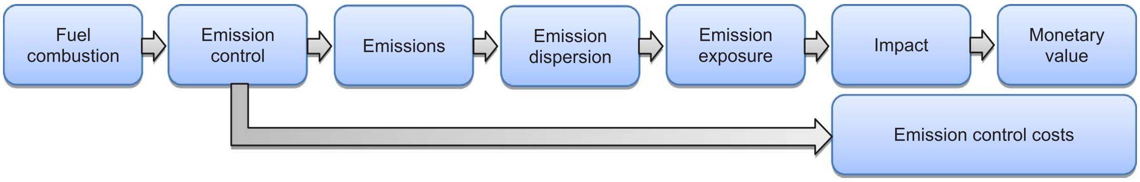

Fig. 1. The impact pathway approach for calculating monetary benefits and emission control costs for each scenario.

Table 1
Scenario description of the BSL and NECA scenarios, BAS = Baltic Sea, NSE = North Sea and the English Channel. NECA implies that all ships built from 2021 comply with Tier III. The NECA-BAS, NECA-NSE, and NECA-BAS + NSE scenarios only affect NO_x emissions.

Scenario name	Scenario description
Baseline (BSL)	The BSL scenario describes expected development of transport volumes, age of ship fleet, use of emission control technologies, emissions, impacts from air pollution, and monetized values of impacts. SECA is implemented through a mix of low-sulphur fuel (~97% of oil use) and use of scrubbers (~3% of oil). LNG propulsion ships corresponds to the fuel purchase volume in statistical data for 2014 (~2% of fuel purchased)
NECA-BAS	As BSL but with NECA implemented in BAS from 2021 through the use of Selective Catalytic Reduction (SCR) or Exhaust-Gas Recirculation & Water in Fuel (EGR + WIF) technologies
NECA-NSE	As BSL but with NECA implemented in NSE from 2021 using technologies as in NECA-BAS
NECA-BAS + NSE	As BSL but with NECA implemented in BAS and NSE from 2021 using technologies as in NECA-BAS
NECA-LNG	As NECA-BAS + NSE but with SECA and NECA requirements met by using LNG propulsion engines on new ships. The potential for using LNG propulsion technologies is ship type specific, but in total LNG fuel constitutes 40% of all fuel use in 2030

2.1. Emissions

We calculate scenario-specific total emissions of NO_X, SO_2, $PM_{2.5}$ (including the sub-fractions BC and OC), CO_2 and CH_4 from shipping in the Baltic Sea and the North Sea for 2030. To do this we first develop a traffic growth model using data on annual fuel efficiency changes, annual traffic changes, and average lifetimes of ships for different ship types from Kalli et al. (2013) (Table A3 and Eqs. (A1)–(A9)). Based on the fixed relationship between fuel use and CO_2 emissions, we used CO_2 emissions as a functional unit of the traffic growth calculations. Eq. (1) explains how CO_2 emissions are calculated for any given ship type constructed in year t:

$$CO_{2_{s,t}} = CO_{2_{s,t-1}} * (1 + tg_s) * (1 - eff_s) \tag{1}$$

where:

$s, t,$ = ship type, year,
CO_2 = CO_2 emissions,
tg = traffic growth,
eff = fuel efficiency increase.

With this model, we calculate the annual fuel use as a progression over time until 2030 (Table 2). The traffic growth model identifies the addition of new, and phase-out of old, ships for different ship types (Table A2). For all scenarios but **NECA-LNG**, we assume that 2% of the fuel that is added each year is LNG, corresponding roughly to the purchases of LNG propulsion ships in SECA in 2014 (UNCTAD, 2013; DNV GL, 2014). Our estimates of ship traffic for 2009 correspond with the 2009 data from Kalli et al. (2013).

With the traffic growth model we also calculate the age distribution of ships in 2030, which is needed to calculate the effect on emissions following an implementation of NECA. We assume that the transport demand and the age distribution of ships are identical for all scenarios. The scenario specifications imply that ships constructed after 2021 follow the Tier II emission standard in **BSL** and

Table 2
Calculated fuel consumption in BAS and NSE in 2030 per ship type.

	BSL & NECA-BAS, -NSE, -BAS + NSE scenarios		NECA-LNG Scenario	
Ship type	Oil use [ktonne]	LNG use [ktonne]	Oil use [ktonne]	LNG use [ktonne]
Bulk carrier	709	14	405	297
Chemical tanker	1587	31	891	653
Container ship	3870	82	2080	1681
General Cargo	1648	30	1614	38
LG tanker	230	4	225	5
Oil tanker	795	16	778	20
RoRo cargo	1243	24	1216	31
Ferry	2187	43	2138	54
Cruise	308	6	301	8

Table 3
Calculated distribution of fuel use per NO_x emission control standards in 2030 (% of fuel used for each ship type).

	BSL scenario			NECA-BAS, -NSE, -BAS + NSE, -LNG scenarios		
Ship type (s)	Tier I	Tier II	Tier III	Tier I	Tier II	Tier III
Bulk carrier	23%	77%	0%	23%	38%	38%
Chemical tanker	23%	77%	0%	23%	38%	38%
Container ship	20%	80%	0%	20%	40%	40%
General Cargo	23%	77%	0%	23%	38%	38%
LG tanker	27%	73%	0%	27%	36%	36%
Oil tanker	23%	77%	0%	23%	38%	38%
RoRo cargo	26%	74%	0%	26%	37%	37%
Ferry	26%	74%	0%	26%	37%	37%
Cruise	26%	74%	0%	26%	37%	37%

the Tier III emission standard in the NECA scenarios; ships that are constructed 2011–2020 follow Tier II in all scenarios; and ships constructed before 2011 follow Tier I. In Table 3 the distribution of fuel consumption between ships in different Tiers is presented for different ship types.

Since NO_x emission standards are specified per engine speed we need to distribute engine types per ship type. Furthermore, emissions are dependent on fuel type so we also need to distribute the fuel type per ship type. To do this we merge and normalise data on the installed engine power for each engine type from ENTEC (2002, 2005b) with data on the distribution of engine types and engine sizes per ship type from Sjöbris et al. (2005) (Tables A4 & A5). We assume that all two-stroke engines are Slow Speed Diesel (SSD) engines and that four-stroke engines are Medium Speed Diesel (MSD) and High Speed Diesel (HSD) engines with the size distribution as follows:

- Large and medium sized four stroke engines are assumed to be MSD when used as main engine.
- Small sized four stroke engines are assumed to be equal shares of MSD and HSD engines.

The resulting distribution of engine type, fuel type, and engine size per ship type are presented in Table A6.

Calculation of disaggregated scenario-specific CO_2 emissions and fuel consumption per ship-, engine-, and fuel type, engine size, and NO_x emission standard is done by combining this distribution with data on fuel consumption per ship type (Table 2) and the distribution of NO_x emission standards (Table 3). NO_x emissions are then calculated by multiplying CO_2 emissions per ship type with the NO_x/CO_2 emission ratio for each ship type and NO_x emission standard (Eqs. (2) and (A11)):

$$NO_{x\,em} = \sum_{s,nct} (CO_{2_s} * N/C_{s,nct} * shnct_{s,nct} + CO_{2-LNG_s} * N/C_{LNG}) \tag{2}$$

where

nct = NO_x emission standard (Tier I, II, III),
N/C = NO_x/CO_2 ratio,
$shnct$ = emission standard share of fuel use per ship type (ratio, see Table 3),
$CO_{2\text{-}LNG}$ = CO_2 emissions from ship with LNG propulsion,
N/C_{LNG} = NO_x/CO_2 ratio for ships with LNG propulsion.

Fur the other pollutants, emissions were calculated as a function of fuel use, which in turn was calculated as a function of CO2 emissions (Eqs. (A12) & (A13)–(A15)). CO_2 emission factors and all emission factors for NO_x and $PM_{2.5}$ emissions from use of marine distillate oil are taken from Cooper and Gustafsson (2004), while BC and OC fractions of $PM_{2.5}$ are taken from Corbett et al. (2010). Emission factors of SO_2 are calculated from the sulphur content of fuel (0.1%), and emission factors for LNG combustion are from Brynolf (2014) (Tables A7 & A8). CH_4 emission factors for LNG propulsion engines are more uncertain than for other pollutants. Part of the reason for this uncertainty is the risk of methane slip (unburnt fuel passing through the engine with the exhaust). The methane slip is in Brynolf (2014) corresponding to 2–4% of LNG use, but there are indications that new engines with lower slip are being developed (Stenersen and Thonstad, 2017). Emissions from land-based European sources are taken from Amann (2014). Land-based emissions are, although important for human health, not the focus of this paper and are therefore kept constant for all scenarios.

We used a web-based literature survey to collect data on the impact on emissions and control costs of existing emission control technologies that meet the Tier I, II and III requirements as well as the SECA requirements. Since ships using LNG propulsion comply with both NECA and SECA requirements it is important to compare the emissions and costs from LNG driven ships with emissions and costs for both conventional Tier III technologies and low sulphur options, including fuel costs. The following SO_2 and NO_x control technologies are included in the cost calculations:

- Advanced Internal Engine Modification (AIEM corresponding to NO_x Tier II);
- Scrubber used with residual oil (RO) with < 2.94% sulphur content;
- Low sulphur (0.1%) fuel use (marine distillates, MD);

- Exhaust Gas Recirculation in combination with Water in fuel injection (EGR + WIF, NO_x Tier III). Tier III might be achieved with only EGR, but due to limited practical experience of EGR, we include WIF in the calculations;
- Selective Catalytic Reduction (SCR, NO_x Tier III);
- LNG Propulsion (NO_x Tier III and < 0.1% sulphur in fuel). LNG propulsion also affects emissions of SO_2, $PM_{2.5}$, BC, OC, CO_2 and CH_4.

Emissions of CH_4, SO_2, $PM_{2.5}$, BC, and OC are assumed not to be affected by the use of SCR or EGR. It is possible that SCR and EGR to some extend would influence the particle emissions but there is not sufficient data to support this and the effect is expected to be small.

2.2. Emission control costs

We calculate the cost for each technology as annual costs consisting of annualised investments (I_{an}), operation & maintenance ($C_{O\&M}$), and fuel penalty costs ($C_{fuel\text{-}p}$) for the target year 2030. Cost estimates from the literature are converted to $€_{2010}$ values.

For AIEM and EGR + WIF we assume that investment costs per kW engine power decrease with increasing size of the engine (ENTEC, 2005b, 2005c). For the other technologies, newer data does not support such an assumption (HELCOM, 2010; Næringslivets NOx-fond and DNV, 2015). We use low, mid, and high fuel prices in 2030 corresponding to on board delivered fuel prices in scenarios developed by the Danish Maritime Authority (DMA) (2012) (Table A15). In addition to investments, SCR technologies require intermittent replacements of the catalytic elements and consumption of urea. Closed scrubbers require the use of NaOH, water, and most scrubbers require sludge disposal. Scrubbers and EGR + WIF incur fuel penalties corresponding to 0.5–2% and 5% of fuel use respectively (Table A16). The cost calculations assume that SCR is only used in combination with MD.

We use data on engine sizes in addition to the cost data to calculate I_{an} (Table A11). We apply a standard annualisation equation (Klimont et al., 2002), to calculate investments as an annual cost per technology. We use an interest rate corresponding to common returns on governmental bonds (pre-financial crisis) of 4% (Godard, 2009). The lifetime of technologies ranges from 12 to 28 years (Table A14).

Costs for fuel (and fuel penalty) as well as for operation and maintenance for each ship type are proportional to the amount of fuel consumed in the NECA. Fuel consumed in NECA in turn depends on the fuel consumed per ship type and on what fraction of the annual hours at sea that each ship type operates within the NECA. Banks et al. (2013) and the Ship Structure Committee (1999) estimate that on average a bulk ship spends about 5700 h at sea per year, a container ship about 5600 h, and a tanker about 5200 h. From this we extract an annual average time at sea of 5500 h for all ships. The voyage pattern varies between ship types: a ferry is likely to remain all year within a NECA, while a large bulk carrier can spend a short period in the NECA. We estimate time spent in the regions for ships with small, medium, and large engines based on the assumption that small ships spend more time in the region than larger ships. The estimates were for some ship types adjusted to give reasonable voyage patterns over all engine sizes. Boundary conditions for this estimation on time spent are data on CO_2 emissions per ship type and number of ships from Kalli et al. (2013). The results can be found in Tables A10, A11 and explained by Eqs. (A16)–(A20).

The distribution of hours between the Baltic and North Seas are calculated to correspond to the regional distribution of 2009 NO_x emissions in Jonson et al. (2014). The resulting scenario-specific numbers of hours in NECA are presented in Table 4.

By multiplying the values in Table 4 with average engine size, engine load factors (ENTEC, 2005a, 2005b) (Table A11), we get the annual energy demand per engine type, fuel type, and engine size (Eqs. (3) & (A25)).

$$kWh_{e,f,ez} = ME_{s,ez}*((hs_{e,f,ez}*lfs)_{ME} + (hm_{e,f,ez}*lfm)_{ME} + (hb_{e,f,ez}*lfb)_{ME}) + AE_{s,ez}((hs_{e,f,ez}*lfs)_{AE} + (hm_{e,f,ez}*lfm)_{AE} + (hb_{e,f,ez}*lfb)_{AE}) \quad (3)$$

Table 4
Assumed annual hours of operation in NECA for the NECA scenarios.

Ship type (s)	Hours at sea in NECA assumed in the NECA-BAS + NSE, and NECA-LNG scenarios			Hours at sea in NECA assumed in the NECA-BAS scenario			Hours at sea in NECA assumed in the NECA-NSE scenario		
	Engine size								
	Small	Mid	Large	Small	Mid	Large	Small	Mid	Large
Bulk carrier	2750	110	110	880	35	35	1870	75	75
Chemical tanker	2750	220	220	880	70	70	1870	150	150
Container ship	2750	935	935	880	299	299	1870	636	636
General Cargo	1375	110	110	440	35	35	935	75	75
LG tanker	2750	165	165	880	53	53	1870	112	112
Oil tanker	2750	440	440	880	141	141	1870	299	299
RoRo cargo	2750	1210	1210	880	387	387	1870	823	823
Ferry	5500	5500	5500	5500	5500	5500	5500	5500	5500
Cruise	2750	1045	1045	880	334	334	1870	711	711

where

e,f,ez = engine type, fuel type, engine size,
ME = main engine effect,
hs, hm, hb = hours at sea; manoeuvring; berth,
lfs, lfm, lfb = engine load factor when: at sea; manoeuvring; berth,
AE = auxiliary engine effect.

The annual energy demand is then used to calculate $C_{O\&M}$ and $C_{fuel\text{-}p}$ (Eqs. (4) and (5) & Eqs. (A30)–(A31)).
$C_{O\&M}$:

$$C_{O\&M_{e,f,ez,nct}} = kWh_{e,f,ez} * (C_{labour} * D_{labour_{ct}} + C_{urea} * D_{urea_{ct}} + C_{cat} * D_{cat_{ct}} + C_{NaOH} * D_{NaOH_{ct}} + C_w * D_{w_{ct}} + C_s * D_{s_{ct}}) \tag{4}$$

where

ct = control technology (both NO_x and SO_2 control),
C = costs per item,
D = demand per item, varying units,
$labour$ = extra work hours needed to use technology
$urea$ = urea (needed in SCR),
cat = SCR catalysts replacement,
$NaOH$ = caustic soda (needed in scrubbers and EGR to reduce SO_2 emissions),
w = water,
s = sludge.

$C_{fuel\text{-}p}$:

$$C_{fuel-p_{e,f,ez,nct}} = kWh_{e,f,ez} * (sfc_{e,f} * C_{fuel_f} * fp_{ct} / 100) \tag{5}$$

where:

sfc = specific fuel consumption
fp = fuel penalty

We then convert I_{an}, $C_{O\&M}$, and $C_{fuel\text{-}p}$ (summed together as C_{tot}) per ship to costs per unit energy content in the fuel while considering engine fuel conversion efficiency (Eqs. (6) & (A32) and Table A17).

$$C_{tcPJ_{e,f,ez,ct}} = \left(\frac{C_{tot_{e,f,ez,nct,sct}}}{kWh_{e,f,ez}}\right) * fuel\ eff_{e,f} \tag{6}$$

where

C_{tc_PJ} = Abatement cost per PJ fuel use,
$fuel\ eff$ = Fuel efficiency of engine.

An example of control costs of technologies available for medium-speed, medium-sized engines using residual oil for the NECA BAS + NSE scenario is presented in Table 5.

Table 5
Annual investment costs (I_{an}), costs for operation and maintenance ($C_{O\&M}$), costs for fuel ($C_{fuel\text{-}p}$) and unit costs for SO_2 and NO_x control technologies in the NECA BAS + NSE scenario for MSD, medium-sized engines using residual oil per energy content in the fuel used.

Technology		I_{an} (10^3 €$_{2010}$/PJ)	$C_{O\&M}$ (10^3 €$_{2010}$/PJ)	$C_{fuel\text{-}p}$ (10^3 €$_{2010}$/PJ)	Unit cost (10^3 €$_{2010}$/PJ)
AIEM	Tier II	48	0	0	48
EGR + WIF	Tier III	355	271	627	1 253
SCR	Tier III	272	211	0	483
LNG propulsion	Tier III	7 440	0	0[a]	7 440
Scrubber new closed (high cost estimate)	-	1 630	1 478	143	3 251
Scrubber new open (high cost estimate)	-	704	90	285	1 079
Scrubber retrofit closed (high cost estimate)	-	2 914	1 478	143	4 534
Scrubber retrofit open, (high cost estimate)	-	1 453	90	285	1 829

[a] For LNG, the propulsion fuel penalty is not relevant as a technology cost parameter. However, the use of LNG propulsion technologies affect the total fuel consumed, and the costs for this are included in the scenario-specific fuel cost calculations, based on fuel consumption (Table 2) and fuel prices (Table A15, DMA, 2012).

Results from Eq. (3) are then multiplied with engine-type specific fuel use (Cooper and Gustafsson, 2004; IMO, 2014) (Table A17) to calculate the scenario-specific fuel consumption per ship type in a NECA. The total scenario-specific cost is given as the product of the scenario-specific fuel consumption multiplied with costs for control technologies and costs for fuel (Eqs. (7) & (A33) and Table A15).

$$Scencost = \sum_{s,e,f,ez,ct} (PJ_{s,e,f,ez,ct} * (C_{tc\,PJ_{e,f,ez,ct}} + C_{fuel_f})) \tag{7}$$

where

$Scen\_cost$ = Costs per scenario
PJ = PJ fuel used per scenario
C_{fuel} = Costs of all fuel used in the scenario

Mid estimates on fuel costs are 12.2, 12.9, and 20.7 million €$_{2010}$ / PJ for LNG, RO, and MD respectively. The cost for NECA is calculated as equal to the total cost of the considered NECA scenario minus the total cost of the **BSL** scenario.

2.3. Emission dispersion

We calculate the atmospheric dispersion of emitted pollutants between regions and countries by using the GAINS model (Amann et al., 2011). The GAINS model is a bottom up integrated assessment model developed to analyse how future air pollution emissions can be reduced to achieve the biggest possible positive impacts on the environment and human health at the lowest cost. In this paper we use the model to calculate emission dispersion. The emission dispersion pattern between regions in the version of the GAINS model used in this paper is a linearized version of results from the EMEP model (Simpson et al., 2012). In the GAINS model, concentration of $PM_{2.5}$ in a recipient grid cell (each grid cell is 28 km * 28 km) is calculated as the product of region and scenario-specific emissions of $PM_{2.5}$, NO_x, SO_2 and NH_3, each multiplied with region- and pollutant-specific source-receptor coefficients Eq. (8), (Amann et al., 2011).

$$PM_j = \sum_i pm_i * PP_{ij} + \sum_i s_i * S_{ij} + \sum_i a_i * A_{ij} + \sum_i n_i * N_{ij} + k_{0,j} \tag{8}$$

where

j,i = recipient grid cell, emitting region,
PM = Annual mean concentration of $PM_{2.5}$ at j,
pm, s, a, n = emissions of primary $PM_{2.5}$, SO_2, NH_3 and NO_x from i,
PP, S, A, N = emission dispersion coefficient matrices for primary $PM_{2.5}$, sulphur, reduced nitrogen, and oxidised nitrogen from $_i$ to $_j$,
k = constant representing background concentration of $PM_{2.5}$ (Amann et al., 2011).

For each scenario we calculate country-specific population-weighted exposure to ambient air concentration of $PM_{2.5}$ in 2030, using population projections from United Nations (2011).

2.4. Health and crop growth impacts

The results on population-weighted annual average exposure to $PM_{2.5}$ are used as input to the Alpha-RiskPoll (ARP) model (Schucht et al., 2015) for calculations of health impacts. The ARP model is a tool for health impact assessment and monetary evaluation of air pollution emissions. The ARP model calculates the health impacts from air pollution by using data specified per relevant age group for population projections (United Nations, 2011) as well as health impact incidence rates and corresponding air pollution concentration-response functions (WHO, 2013). The air pollution impact for a scenario corresponds to the increase of incidence rate for the considered health impacts as a function of calculated $PM_{2.5}$ concentrations. Impacts on mortality are calculated as both the number of fatalities and the aggregate reduction in life expectancy across the population, providing alternative metrics of impact for use in subsequent sensitivity analysis. The other age-group specific health impacts considered are: asthma symptom days (age group 5–19); bronchitis in children (6–12); cardiovascular hospital admissions (18+); chronic bronchitis (27+); lost working days (15–64); respiratory hospital admissions (all ages); and restricted activity days (all ages). In this paper we do not include any direct health impact from exposure to NO_2 (Faustini et al., 2014) or the suspected relatively high importance of black carbon particles for health impacts (WHO, 2012) due to risk of double-counting with health impacts from exposure to $PM_{2.5}$. Neither do we include health impacts from exposure to ozone. Crop growth impacts are included through the impacts on crop growth from ozone as indicated by region-specific NO_x emission levels (Holland et al., 2011). Climate change impacts are of relevance in **NECA-LNG** and estimated by comparing impact on CO_2 emissions with low, mid, and high values of CO_2 equivalents for the short-lived climate pollutants (SLCP) CH_4, SO_2, BC, OC. We thus use the climate metrics GWP_{100} and GTP_{20} estimated for European emissions, and global average values of GWP_{20}, as factors for calculating CO_2 equivalents for the SLCP emissions. (Myhre et al., 2013a, 2013b) (Table 6). Due to lack of information we assume the climate impact of non-carbon $PM_{2.5}$-fractions (Other $PM_{2.5}$) as identical to impact of SO_2.

Table 6
Climate metrics of pollutants affected by LNG propulsion used in this paper (Myhre et al., 2013a, 2013b). We assume that the climate impact of 'Other $PM_{2.5}$' is identical to that of OC.

Climate metric/pollutant	GWP_{100}	$GTP_{20(Europe)}$	GWP_{20}
CH_4	28	67	84
SO_2	−40	−29	−140
BC	138	230	480
OC	−26	−39	−92
Other $PM_{2.5}$	−40	−29	−140

Climate change impacts of NO_x emissions are omitted due to the opposing impacts dependent on metric (metric values are -15, 6, −48, and 19 for GWP_{100}, GTP_{20}, and GWP_{20} respectively).

2.5. Monetizing health and crop growth impacts

The monetized values of health impacts are taken from an earlier study carried out for the European Commission (Holland, 2014). The highest health impact value, the value of statistical life (VSL), range between 1,218,000–3,130,000 €$_{2010}$ per avoided fatality from reduced exposure to air pollution (45,000–155,000 €$_{2010}$ if expressed as Value Of Life Year lost (VOLY)) (Holland et al., 2005; Desaigues et al., 2011; OECD, 2012; Holland et al., 2013; CBI, 2011). We use these ranges in our analysis and the low range in our benefit assessment is the lowest value of VOLY, the mid-range is the highest value of VOLY, while the high range value is based on calculations of avoided fatalities using the highest VSL value. The mid-range is then more conservative than the recommended value by OECD (2012). The low-range is conservative, but is retained for consistency with Holland (2014). The monetized value of avoided crop damages is dependent on recipient region and is estimated to range between 35 and 146 €$_{2010}$/tonne NO_x (Holland et al., 2011). Climate change can also have impacts on crop growth, but we assume that this impact is included in the economic values of climate change. Climate change impacts in **NECA-LNG** are valued using recent EU ETS prices (7 €$_{2010}$/tonne CO_2), projected 2030 EU ETS prices for the EU climate and energy strategy (53 €$_{2010}$/tonne CO_2 (European Commission, 2014)) and the Swedish CO_2 tax (105 €$_{2010}$/tonne CO_2) as low, mid and high values, respectively. We exclude monetary impacts on acidification, eutrophication, biodiversity, and other ecosystem services since the relationship between emission reductions and monetary losses is yet to be estimated. The benefits of NECA in 2030 are calculated as equal to the total monetary value of air pollution damages in the **BSL** scenario minus the corresponding total monetary value in the NECA scenario.

2.6. Comparing costs with benefits

To account for uncertainty we present a range of costs and benefits for each scenario and also benefit/cost ratios for all cost assessments and all benefit assessments. There are also uncertainties in the emission factors but these are likely small in relation to the variation in the monetized values for health impacts. The main exception is the emission factor for CH_4 from LNG engines where only few measurements are available. For the NECA scenarios, costs are calculated for ranges covering varying Tier III technology choices (RO & EGR + WIF or MD & SCR or a mix), and varying fuel prices (Table A15, (DMA, 2012)). For **NECA-LNG**, there is a larger uncertainty in costs. Both since LNG propulsion is a relatively new technology and since the costs of NECA and SECA if using LNG propulsion are affected by the **BSL** cost of using scrubbers to reach SECA requirements. Correspondingly in **NECA-LNG** costs are calculated for ranges covering varying investment costs for LNG technology and varying costs and fuel efficiency of scrubbers. For all scenarios the benefits are, as described in Section 2.6, varied with respect to: the value of avoided mortality; impacts on climate change from CO_2 and SLCP emissions; and monetary value of climate change impacts. From the above variations we select the low, mid and high assessments of costs and benefits to be used in the benefit/cost ratio calculations.

3. Results

3.1. Scenario-specific emissions

The results related to emissions are seen in Table 7, which present emissions of NO_x, $PM_{2.5}$, SO_2, CO_2, CH_4 for all scenarios and emission reductions compared to the **BSL** scenario. As is seen, the impact of NECA on emissions will be dependent on to what extent LNG engines will be used to meet the requirements.

NO_x emissions would be reduced in 2030 by an implementation of a NECA in 2021 for all scenarios: the reduction range is 22–26% in the respective region for **NECA-BAS**, **NECA-NSE**, & **NECA-BAS + NSE,** and 39% in **NECA-LNG**. The emission reduction of BC and OC corresponds to 25% and 28% of the $PM_{2.5}$ emission reductions in **NECA-LNG**. The use of LNG propulsion will involve some level of methane slip through the engines. Available estimates are uncertain due to limited information on emission factors and because LNG propulsion is a new technology. While acknowledging the uncertainty regarding methane slip our results show that **NECA-LNG** imply an increase in greenhouse gas emissions of 2.3–6.9 million tonne CO_{2eq} in a 100 & 20 year perspective from increased CH_4 emissions in BAS and NSE, and the net effect of the emission reduction of other SLCP emissions would imply an increase in climate change impacts of another 0.2–0.8 million tonne CO_{2eq}. Including the decrease in CO_2 emission the net climate

Table 7
Scenario-specific BAS and NSE emissions of NO_x, $PM_{2.5}$, SO_2, CO_2, CH_4 and emission reduction compared to the BSL scenario.

Scenario	2030 Emissions [ktonne]					2030 Scenario emission reduction compared to BSL scenario [ktonne]				
	NO_x	$PM_{2.5}$	SO_2	CO_2	CH_4	NO_x	$PM_{2.5}$	SO_2	CO_2	CH_4
BSL										
Baltic Sea	241	2	8	12 900	2.4[a]	–	–	–	–	–
North Sea	507	4	17	27 100	5.1[a]	–	–	–	–	–
NECA-BAS										
Baltic Sea	178	2	8	12 900	2.4[a]	46	0	0	0	0
North Sea	507	4	17	27 100	5.1[a]	0	0	0	0	0
NECA-NSE										
Baltic Sea	241	2	8	12 900	2.4[a]	0	0	0	0	0
North Sea	376	4	17	27 100	5.1[a]	122	0	0	0	0
NECA-BAS + NSE										
Baltic Sea	178	2	8	12 900	2.4[a]	46	0	0	0	0
North Sea	376	4	17	27 100	5.1[a]	122	0	0	0	0
NECA-LNG										
Baltic Sea	147	2	6	12 300	30[a]	77	0[b]	2	600	−28
North Sea	311	3	13	26 000	60[a]	187	1	4	1100	−55

[a] CH_4 emission factors are more uncertain than emission factors for other pollutants.
[b] The reduction of primary $PM_{2.5}$ in the Baltic Sea is too small to be included in the benefit analysis.

impact of **NECA-LNG** compared with **NECA-BAS + NSE** is a warming impact corresponding to 0.8–6.0 million tonne CO_{2eq} dependent on time horizon and mostly due to methane slip.

3.2. Costs and benefits

In general, the benefits of NECA in 2030 would be larger than the corresponding costs, although with considerable variation (Table 8).

The costs of NECA in Table 8 includes costs for use of control technology as well as costs for fuel use in comparison to corresponding costs for the **BSL** scenario. The costs are low compared to the **NECA-BSL** total fuel costs of about 2200 M€$_{2010}$, 4900 M€$_{2010}$, and 7100 M€$_{2010}$ for BAS, NSE, and BAS + NSE respectively. The control cost per tonne NO_x reduced (unit cost) declines with the number of hours a ship operates within the NECA: for **NECA-BAS**, the unit cost would correspond to about 2400 €$_{2010}$/tonne NO_x, for **NECA-NSE** 1500 €$_{2010}$/tonne NO_x, and for **NECA-BAS + NSE** 1400 €$_{2010}$/tonne NO_x. The relatively low costs for LNG fuel and improved fuel efficiency of LNG propulsion engines drive down the control costs in the **NECA-LNG** scenario.

The B/C ratios of the **NECA-NSE** and **NECA-BAS + NSE** are for all combinations of benefits and costs higher than one (Fig. 2).

For **NECA-BAS** the B/C ratio is lower than one for all variations with low monetized values of air pollution benefits. Overall, the B/C ratio depend most strongly on the choice of low, mid, or high values for air quality benefits.

For **NECA-LNG** the B/C ratios are mixed, but with a majority of the ratios being over one.

The only assessments (3 of 27) where **NECA-LNG** costs are higher than benefits are in the specific situations where air pollution benefits are valued low, negative climate change impacts of SLCP emissions are large, and the economic value of climate change is valued high, all at the same time (see Fig. 3).

Table 8
Mid estimates of 2030 costs and monetized benefits of NECA in the Baltic Sea and the North Sea (min and max values in parenthesis).

Scenario	Control costs [10^6 €$_{2010}$]	Monetized benefits [10^6 €$_{2010}$]
NECA-BAS	111 (100–123)	139 (56–294)
NECA-NSE	181 (157–209)	869 (335–1882)
NECA-BAS + NSE	230 (195–273)	1007 (392–2177)
NECA-LNG	153 (88–238)	1549 (47–3795)

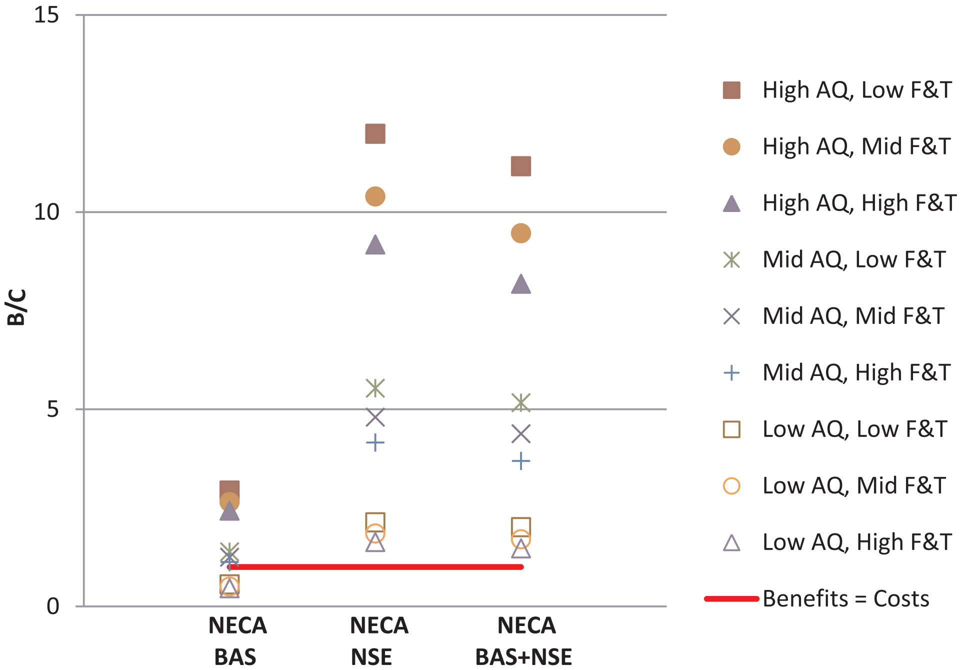

Fig. 2. Benefit/Cost ratios for NECA-BAS, NECA-NSE, NECA-BAS + NSE. AQ indicates monetized benefits of improved air quality; F&T is an abbreviation for Fuel and Technology costs. The red line indicates the level above which a NECA implies a net benefit for society.

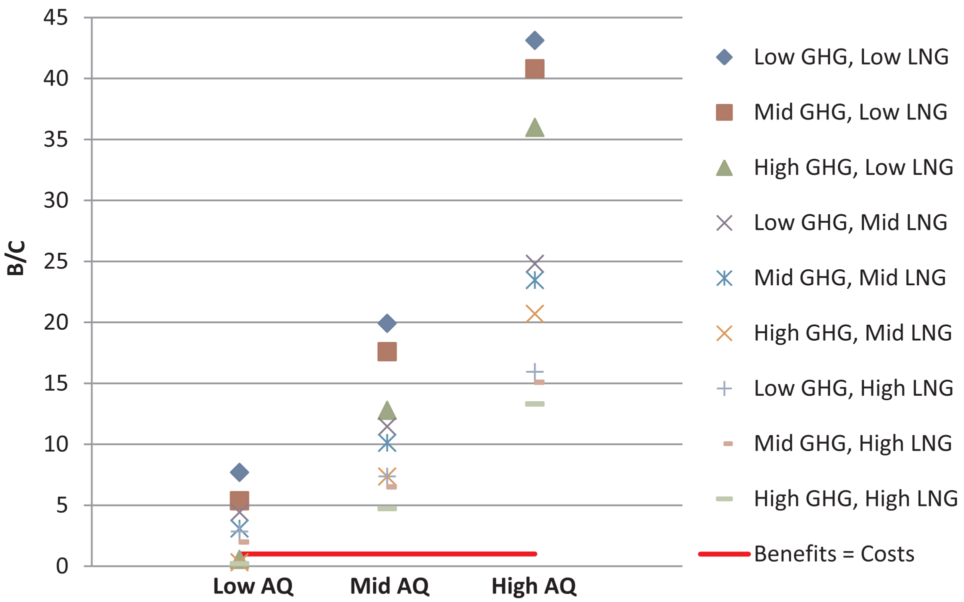

Fig. 3. Benefit/Cost (B/C) ratios for the introduction of LNG propulsion engines as a primary way to meet NECA + SECA requirements. The ratios are grouped on the x-axis according to which estimate of air pollution benefits that was used (Low AQ, Mid AQ, High AQ). The term GHG depicts which climate metric that was used and which economic value that was ascribed to climate change. The term LNG includes the calculations based on high scrubber costs in the BSL scenario (Low LNG), the mid estimate (Mid LNG), and high investment costs for LNG propulsion (High LNG).

4. Discussion

In this paper, we analyse the net socio-economic impacts in 2030 for Europe of a NECA in either the Baltic Sea or the North Sea, or both sea regions. The results from our analysis suggest that if the introduction of a NECA does not affect transport demand or the age distribution of the ships servicing the Baltic and North Seas the total annual monetised benefits in 2030 of NECA implemented 2021 would be 2–12 times higher than the total annualised costs for the North Sea and 1.5–11 times higher for both sea regions. A NECA in just the Baltic Sea is not given as strong support from the analysis, with benefits ranging between 0.5 times the costs if using low valuation of mortality to 3 times the costs if using high valuation. When looking at the details of the results one can see that for two thirds of the scenarios analysed for the Baltic Sea, a NECA would give benefits higher than costs. Also, as noted above, the lower valuation of mortality seems increasingly conservative, with support growing for the mid and higher end of the range. We also find that an introduction of LNG propulsion technology in ships as a response to NECA could give even higher benefits and lower costs. However, the best estimate of methane slip associated with LNG propulsions is uncertain, and the large time dependent variation of climate impacts from SLCP emissions and associated variation in monetary values cause higher variation in benefit estimates compared to the other scenarios. In our LNG scenario, benefits range between 0.2 up to 43 times the costs with 24 out of 27 assessments having benefits larger than costs.

Due to limited research in this field only some of our results can be compared with other studies. Our baseline NO_x emission results for the Baltic and North Seas (748 ktonne NO_x in 2030) are somewhat lower than in previous studies. Jonson et al. (2014), Kalli (2013), and Kalli et al. (2013) estimate NO_x emissions in 2030 to 935, 840, and 770 ktonne respectively. In our results, a NECA in the Baltic and North seas would decrease NO_X emissions in 2030 to 554 ktonne (26% lower than the baseline in 2030), similar to the estimates of the relative impact of a NECA in Kalli (2013): 25% reduction to 640 ktonne in 2030. However, it is less than the 29% reduction estimated by Winnes et al. (2016). Our cost estimates range between 1440–2800 €$_{2010}$/tonne NO_x dependent on scenario, which is in line with some previous studies. Campling et al. (2013) estimate lower costs (around 660 €$_{2010}$/tonne NO_x), while DEPA (2012) and Hammingh et al. (2012) estimate costs for reducing emissions from ships in the North Sea to be in the range of 890–2910 €$_{2010}$/tonne NO_x. Our cost estimates are likely to be in the high end since we do not include any learning effects (the reduction in costs as a function of earlier investments). All technologies we consider in this analysis are relatively new and have yet to be installed in large numbers. It should therefore be anticipated that costs could go down even more through learning.

Our benefit estimates of human, crop growth, and climate impacts of emission reductions mainly focus on human health and climate impacts and are likely to be in the low end. It is yet not feasible to monetize benefits of reduced pressure on acidification, eutrophication, or biodiversity on the regional scales necessary for this CBA. The monetization of health impacts is also incomplete since there are more health impacts linked to ambient $PM_{2.5}$ than the ones included in our study, such as impacts on low gestational weight at birth (Thurston et al., 2017). Furthermore, there is now also widening recognition that exposure to NO_2 in itself (in contrast to NO_2 being an indicator of other pollutants) cause adverse health impacts (Faustini et al., 2014). This risk is not included in our analysis. All of the above indicate that our estimates of benefits of emission reductions are underestimations. There is however also concerns that primary $PM_{2.5}$ (BC) might be more harmful to human health than secondary $PM_{2.5}$ (nitrates inter alia). If these concerns would become validated in the future, our benefit estimates would prove to be overestimations. Our current judgement is that on the balance our benefit estimates of the NECA scenarios are underestimations.

If LNG propulsion technologies are adopted extensively, emissions of air pollutants and CO_2 would decrease while CH_4 emissions may increase, implying increasing net climate change impacts corresponding to 0.8–6.0 million tonne CO_{2eq}, with the range explained by the time perspective chosen (the 20- or 100-year horizons for global warming potential). The methane slip from engines is estimated to imply an increase in climate change impact of 2.3–6.9 million tonne CO_{2eq} from the use of LNG propulsion technologies in the Baltic and North Sea regions, and is the dominating driver of negative climate impacts of LNG propulsion. However, the estimates are uncertain and technology development can have a strong impact on the level of methane slip.

Our B/C estimates include variation in control costs, the monetized value of avoided fatalities, climate impacts of SLCP emissions, and monetized values of climate impacts. For all NECA scenarios, the monetized value of avoided fatalities explained most of the variation in B/C ratio. It is, however, also important to increase the certainty about the emission factor for CH_4 from LNG engines.

Potential impacts on transport demand and the associated risk of shifting transport from ships to land-based modes of transport was debated during the years leading up to the stricter SECA requirements (AMEC Environment & Infrastructure UK Limited, 2013). Since that debate this risk has been reduced by lower prices on residual oil and marine distillates. To what extent a NECA would affect transport demand remains to be analysed, but our results show that the costs of NECA are around 3% of total marine fuel costs in the region. In comparison, Jonson et al. (2014) assess that a SECA implemented using low sulphur fuel would increase fuel costs with 30–80%. At the same time, Holmgren et al. (2014) consider modal back shift as unlikely for high-value container goods as a response to SECA, while an earlier study (Notteboom, 2010) saw a risk for impacts on RoRo shipping (although partly based on self-reporting during 2009 when fuel prices were high). Our overall impression based on cost impacts and the literature is that a NECA is less likely to have significant impacts on the transport patterns, compared to what has been suggested for SECA in the literature.

There is also a risk that ship owners would choose to re-assign older ships to the North and Baltic seas in response to NECA requirements only applying to new ships, or that there will be a construction 'boom' during 2019/2020. Whether this will happen remains to be seen, but the effect would be that both the costs and benefits of NECA would be smaller, so the B/C ratio should remain relatively stable. A factor – not discussed in this paper - that could constrain the possibility to re-assign older ships to the Baltic and North Seas can be safety regulations.

All in all we have chosen a conservative approach in the cost-benefit analysis with probably over-stated costs and understated benefits. We therefore consider the policy recommendations from this paper to be robust.

Since our cost estimates are functions of annual hours of operation within a NECA, we could show that the larger the NECA region, the lower the unit cost of emission control. This is due to a higher number of operational hours of the abatement equipment per ship when the NECA region is larger. A potential counteracting mechanism could be if a NECA would be expanded to include regions dominated by ships that spend little time in the NECA or in other NECAs. This observation has an important consequence: if more regions implement NECA in addition to Northern Europe and the U.S & Canada, it is probable that unit costs will go down.

4.1. Implications

In this paper we present detailed cost data and a method for calculating costs and impacts on emissions from SCR, EGR, Scrubbers, and LNG propulsion used to control emissions from ships (for details see the supplementary material). By transparently presenting the method and all numerical values collected by us over the years we hope that we are helping future analysis.

NECA as a policy instrument to reduce the negative health impacts from air pollution can from a socio-economic perspective be justified by our analysis. And the option to use LNG propulsion gives more flexibility and should enable costs to go down, largely due to fuel efficiency and comparatively low LNG fuel prices. Further technological development of LNG propulsion engines is important, however, to ensure that methane slip is minimized to avoid trade-off between climate and air pollution.

Our results gives socio-economic justification of NECA in the Baltic and North seas, and show that unit control costs go down significantly the more the control technology is used. Given these results and the fact that NECAs in these regions have been approved, it is reasonable to further analyse the socio-economic effects of NECAs in other sea regions close to densely populated areas, such as the Mediterranean Sea or the Bay of Biscay. More regions than those studied in this paper probably have favourable benefit/cost ratios of NECAs, especially now that there are NECAs in Northern Europe, the U.S., and Canada.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2017.12.014.

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